



University
of Glasgow

HIGH-FREQUENCY COMMUNICATION SYSTEMS

Lecture 5

Hasan T Abbas & Qammer H Abbasi

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- Array Directivity
- Planar Antenna Arrays
- Feeding Networks
- Software-defined Radio

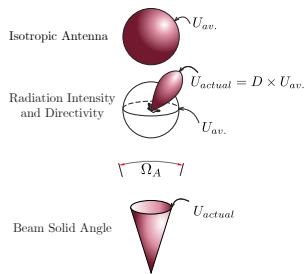
DIRECTIVITY

- Recall *directivity* describes the antenna radiation in a given direction
- We use the *radiation intensity* $[U(\theta, \phi) = 1/2 \operatorname{Re}(\vec{\mathbf{E}} \times \vec{\mathbf{H}}^*) \cdot r^2 \hat{\mathbf{r}}]$ to assess the power radiated in a given direction **per unit solid angle**
- We define directivity as:

$$D = \frac{4\pi}{\Omega_A}$$

$$\text{where, } \Omega_A = \oiint |EF(\theta, \phi)|^2 |AF(\theta, \phi)|^2 d\Omega$$

$$d\Omega = \sin \theta d\theta d\phi$$



Let us consider a uniformly excited, uniformly spaced linear array where all the elements are *isotropic* ($EF = 1$). From the previous lecture, we got:

$$|AF|^2 = \left| \frac{\sin N\psi/2}{N \sin \psi/2} \right|^2 \equiv \frac{1}{N} + \frac{1}{N^2} \sum_{m=1}^{N-1} (N-m) \cos m\psi \quad (1)$$

Knowing,

$$\psi = kd \cos \theta + \alpha \implies \sin \theta d\theta = -\frac{1}{kd} d\psi$$

The beam solid angle Ω_A then becomes:

$$\begin{aligned} \Omega_A &= \int_0^{2\pi} d\phi \int_0^\pi |AF(\theta)|^2 d\theta = 2\pi \int_{kd+\alpha}^{-kd+\alpha} |AF(\psi)|^2 \left(\frac{-1}{kd} \right) d\psi \\ &= \frac{2\pi}{kd} \int_{-kd+\alpha}^{kd+\alpha} |AF(\psi)|^2 d\psi \end{aligned} \quad (2)$$

Solving (1) and (2) we get:

$$\begin{aligned}
 \Omega_A &= \frac{2\pi}{kd} \left[\frac{1}{N} \int_{-kd+\alpha}^{kd+\alpha} d\psi + \frac{2}{N^2} \sum_{m=1}^{N-1} (N-m) \int_{-kd+\alpha}^{kd+\alpha} \cos m\psi d\psi \right] \\
 &= \frac{2\pi}{kd} \left[\frac{1}{N} \psi \Big|_{-kd+\alpha}^{kd+\alpha} + \frac{2}{N^2} \sum_{m=1}^{N-1} (N-m) \frac{\sin m\psi}{m} \Big|_{-kd+\alpha}^{kd+\alpha} \right] \\
 &= \frac{2\pi}{kd} \left[\frac{1}{N} (2kd) + \frac{2}{N^2} \sum_{m=1}^{N-1} \frac{N-m}{m} [\sin m(kd + \alpha) - \sin m(-kd + \alpha)] \right]
 \end{aligned}$$

Using the trigonometric identity, $\sin(a + b) = \sin a \cos b + \cos a \sin b$, we get:

$$\Omega_A = \frac{4\pi}{N} + \frac{4\pi}{N^2} \sum_{m=1}^{N-1} \frac{N-m}{m} \frac{1}{kd} 2 \cos m\alpha \sin mkd$$

The directivity for the broadside and end-fire arrays is thus:

$$D = \frac{4\pi}{\Omega_A} = \frac{1}{\frac{1}{N} + \frac{1}{N^2} \sum_{m=1}^{N-1} \frac{N-m}{m k d} 2 \cos m\alpha \sin m k d}$$

For arrays such as the *Hanson-Woodyard* arrays, there is an additional renormalisation factor that accounts for the **excess phase delay, δ** ,

$$D_{\text{General}} = \frac{\left| \frac{\sin(N\delta/2)}{N \sin \delta/2} \right|^2}{\frac{1}{N} + \frac{1}{N^2} \sum_{m=1}^{N-1} \frac{N-m}{m k d} 2 \cos m\alpha \sin m k d} \quad (3)$$

In general, the directivity from (3) can be visualised as:

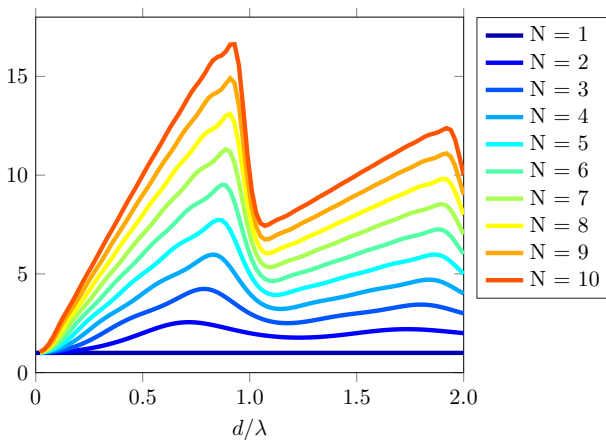


Figure 1: Seeing the directivity as a function of element spacing d and number of elements N .

MULTIDIMENSIONAL ARRAYS

- So far, the 1D arrays we have looked at only yield beamscanning along one angle θ .
- Using multidimensional arrays, we can:
 - Obtain pencil beams
 - Higher directivity and gain
 - Manoeuvre beams in both elevation and azimuthal planes.
- We can have elliptical or rectangular shapes in the 2D case

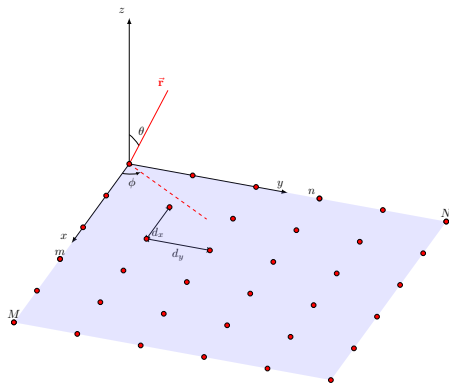


Figure 2: A 2D rectangular array.

Generally, the Array Factor for a 3D array can be described by first expressing the elements in the form of a position vector:

$$\hat{\mathbf{r}}_{mn} = \hat{\mathbf{x}} d_{mn} + \hat{\mathbf{y}} y'_{mn} + \hat{\mathbf{z}} z'_{mn}$$

Then,

$$AF(\theta, \phi) = \sum_{m=1}^M \sum_{n=1}^N I_{mn} \exp\left(j(k \hat{\mathbf{r}} \cdot \hat{\mathbf{r}}_{mn} + \alpha_{mn})\right)$$

In the normalised form, we can write AF as:

$$AF(\theta, \phi) = \frac{\sin M\psi_x/2}{M \sin \psi_x/2} \frac{\sin N\psi_y/2}{N \sin \psi_y/2}$$

where,

$$\psi_x = kd_x \sin \theta \cos \phi + \alpha_x$$

$$\psi_y = kd_y \sin \theta \sin \phi + \alpha_y$$

Considering a 5×5 planar array with element spacings $d_x = d_y = \lambda/2$ and the phases $\alpha_x = \alpha_y = -\pi/(2\sqrt{2})$. The radiation pattern looks like this:

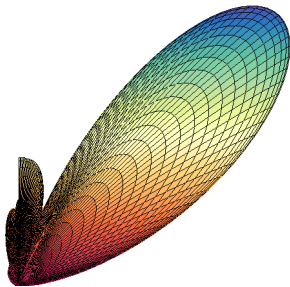


Figure 3: Radiation Pattern in the Cartesian coordinates.

FEEDING NETWORKS

- The main benefit of phased array antennas is there is no need for *mechanical motion*.
 - Beam can be steered using electronics
- A disadvantage is each antenna element *must* have a transmission path to the receiver
 - This is done both via hardware and software



Figure 4: Feeding Cables out of a Massive MIMO Phased Array Antenna

- Most common feeding network
 - Also called *parallel feed*
- We have equal line lengths for each element
 - Phase and amplitude are the same across the elements
- Corporate feed can be operated at many frequencies
 - We call it wideband as the operation is independent of frequency

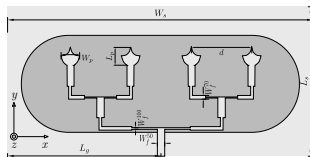
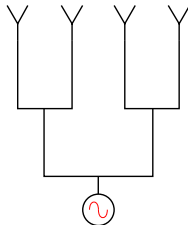


Figure 5: A Planar Inverted Cone Antenna Array ¹.

¹Abdoalbaset al Abohmra et al. "An Ultrawideband Microfabricated Gold-based Antenna Array for Terahertz Communication". In: IEEE AWPL (2021). ISSN: 1548-5.

- The Simplest feeding architecture
 - Phase difference can be easily generated
- However, practically loss occurs along the series line
 - This results in unequal amplitudes across the elements
- By changing the frequency, the electrical line length of the feed is changed.
 - Due to this, we have dispersion that limits bandwidth

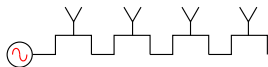


Figure 6: A series feeding network.

- Suitable for very large arrays
 - Additional phase shift is introduced commonly through diodes (PIN etc.)
- MEMS-based switches can turn a particular arm on or off.
 - Such feeds can withstand high-power inputs

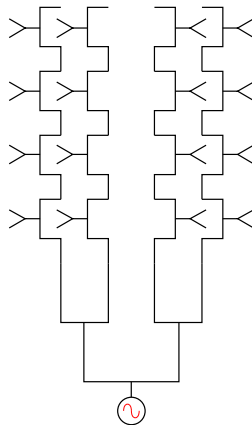


Figure 7: A hybrid corporate-series feeding network.

- For millimetre wave communications, corporate, and series feeding architectures become very complicated
- Other techniques such as *sequentially rotated phase* feeding networks are emerging as attractive candidates
 - Each antenna element is physically rotated
 - Additionally, there is a phase shift to each element
- The advantage over corporate feeding network is that the *resonant* response can be obtained at a higher range of frequencies
 - Ensures radiation pattern integrity

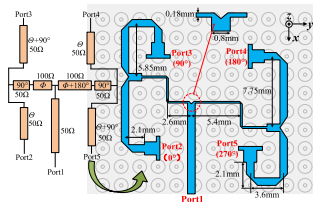


Figure 8: A sequentially rotated phase feeding network

¹Chaojun Ma, Zu-Hui Ma, and Xiupu Zhang. "Millimeter-Wave Circularly Polarized Array Antenna Using Substrate-Integrated Gap Waveguide Sequentially Rotating Phase Feed", In: IEEE AWPL (2019). ISSN: 1548-5757.

SOFTWARE DEFINED RADIO

- A communication system consists of many layers of operations.
- The physical layer is the most important of all.
- Typically, physical layer processing is done via dedicated hardware
- Radio is the technology through which signals are wirelessly transmitted and received
- Software-defined radio has some or all physical layer functions implemented via software

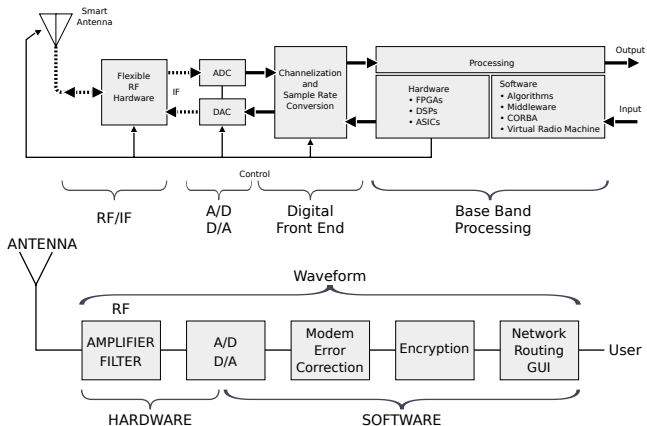


Figure 9: A Typical SDR workflow

- A graphical user interface consisting of *flowgraphs* through which different signal processing functions such as analogue-digital conversion can be performed.
- Some additions let us write **Python** codes within each block
- The software is meant to interface with Universal Software Radio Peripheral (USRP) modules to construct a complete communication system.

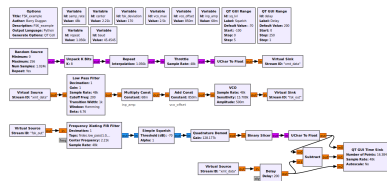


Figure 10: GNU Radio Interface.